Intermediate Project

Pitot tube for air velocity measurement

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1 Abstract

Objective of a project was to construct a Pitot tube based on two atmospheric barometers and STM32 microcontroller. Usually a single differential pressure barometer is used, but such devices are very expensive in comparison to absolute value digital pressure sensors like BMP280. It was assumed that two single channel barometers can replace differential one, achieving decent accuracy in very low cost application. As a result, Pitot tube was made and tested. Tests shown that while tube can measure air flow, it's readings are very susceptible to errors caused by wind, air disturbances and angle of incoming air direction.

2 Pitot tube working principle

This page shows a schematic drawing of a Pitot tube. Several small holes are drilled around the outerpipe the tube and a center pipe is going down the axis of the tube. The outside pipe is connected to one input of differential pressure sensor. The center pipe in the tube is kept separate from the outer one and is connected to the other input of the sensor. The transducer measures the difference in pressure in the pipes of the tube by measuring the strain in a thin element using an electronic strain gauge. The pitot tube is mounted on the object so that the inner pipe is always pointed in the direction of travel and the outside holes are perpendicular to the tube.

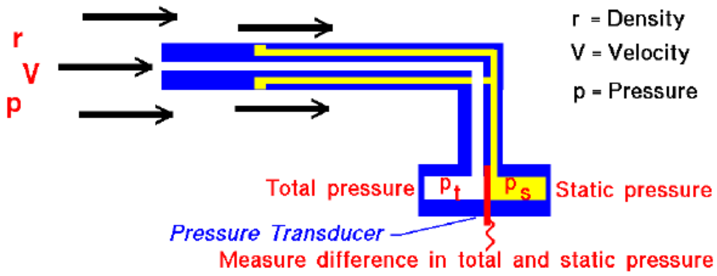

Figure 1: Breakout board with BMP280 sensor

Since the outside holes are perpendicular to the direction of movement, these inner pipe is pressurized by the local atmospheric pressure. The pressure in these tube is the static pressure in Bernoulli's equation. The center tube is pointed in the direction of travel and is pressurized by both the static pressure and the pressure generated by air velocity. The pressure in this tube is the total pressure in Bernoulli's equation. The pressure transducer measures the difference in dynamic and static pressure.

$$P_{static} + r * \frac{v^2}{2} = P_{total}$$

From Bernoulli's equation it is possible to calculate velocity.

$$v = \sqrt{\frac{2(P_{total} - P_{static})}{r}}$$

3 Pitot tube applications

Pitot tube is widely used to determine the airspeed of an aircraft, water speed of a boat, and to measure liquid, air and gas flow velocities in certain industrial applications. In a picture in fig.2 Pitot tube is mounted on a wing of a small airplane. Small versions of Pitot tubes are also used as airspeed sesnors in UAVs.

Figure 2: Pitot tube on a wing of small plane

Figure 3: Pitot tube on a UAV

4 Project goal and assumptions

As a pressure sensor usually a differential pressure transducer is used. However, such devices are very expensive in comparison with atmospheric pressure barometers like BMP80. In this project two barometers were utilized as a separate pressure transducers. Their readings were subtracted to calculate differential pressure.

5 BMP280 barometric pressure sensor

It was decided to use BMP280 barometric pressure sensor as a pressure transducer[1]. It supports I^2C and SPI - two most common digital interfaces in microcontrollers. Most important features of BMP280 are listed in table 5.

Parameter	Symbol	Min	Typical	Max	Unit
Operating temperature range (for full accuracy)	T	-40	25	+85	°C
Temperature accuracy	ΔT		1.0		°C
Operating pressure range	P	300		1100	hPa
Pressure accuracy	ΔP		1.0		hPa
Possible sampling rate	$f_{sampling}$			157	Hz

Table 1: Pressure sensor parameters

Using sensor with digital interface makes system less sensitive to any noise that occurs in analog circuits. In I^2C mode it can be connected to microcontroller using only two wires. On-chip controller can perform some task, like temperature compensation and simple data filtering. Although sensor is optimized to achieve low power consumption for a cost of lower sampling frequency, it can be configured to read data in periods lower than 10ms. As long as reading data from sensors is sequential, measurement time has to be kept low. In other case, pressure could change slightly between reference and dynamic pressure readings. In such a situation, result of air velocity calculation would be incorrect.

Despite good measurement range and accuracy, BMP280 sensor is dedicated to barometric pressure measurement. It wasn't previously used in a scenario, where two sensors work as a replacement of a single differential one.

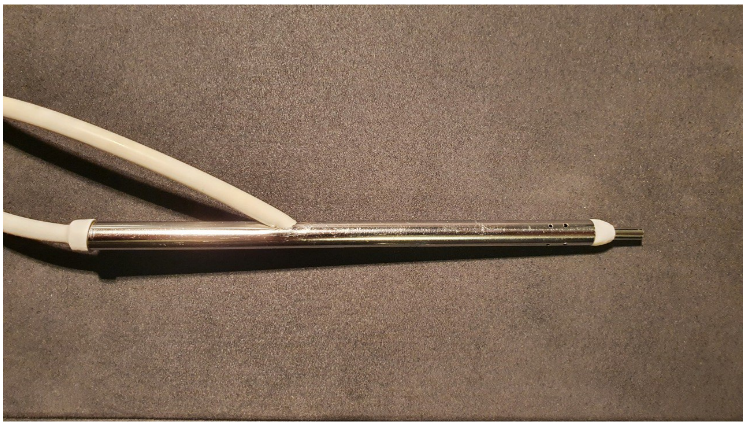

Figure 4: Pitot tube used in a tests

6 Interfacing sensors with STM32 microcontroller

Both sensors were interfaced with microcontroller with I^2C bus running at 400kHz frequency. Each sensor runs on a separate I^2C bus, so they don't interfere with each other under any circumstances. It is possible to read data from both sensors in parallel. It can be done using RTOS or DMA, but because of high measurement frequency it may be not necessary. Measurement are taken in 10ms intervals, which corresponds to 100Hz frequency.

As a microcontroller unit STM32F411 on Nucleo development board was chosen. Main advantages of using this boards are:

- 3 separate I^2C buses,
- embedded FPU allowing fast floating point operations,
- 128kB RAM and 512kB FLASH memory,
- embedded ST-Link programmer, with UART-USB converter.

For initial tests Nucleo board and sensors were connected on prototyping board. Picture 5 shows two breakout boards with BMP280 sensors and Nucleo board with STM32F411 MCU. Pull-up resistors for I^2C buses are included in BMP280 breakout boards.

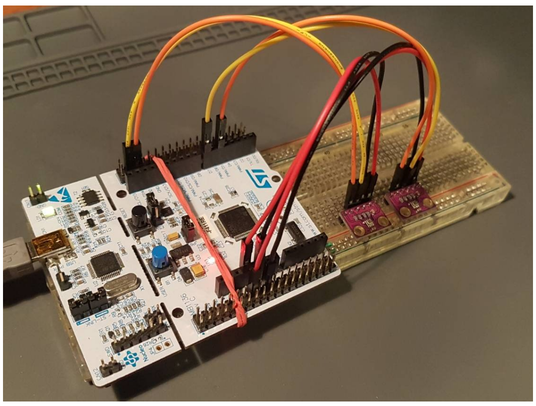

Figure 5: Sensors attached to Nucleo board

7 Filtering data

Pressure sensor has ability to filter data by itself using simple IIR filter. Filter allows to cut high-frequency disturbances, but slows down response for pressure changes. Filter coefficients can be configured to values from 0 (filter off) to 16. Filter response for sudden pressure change was tested for 0, 8 and 16 values. Results are shown on figures 6, 7 and 8.

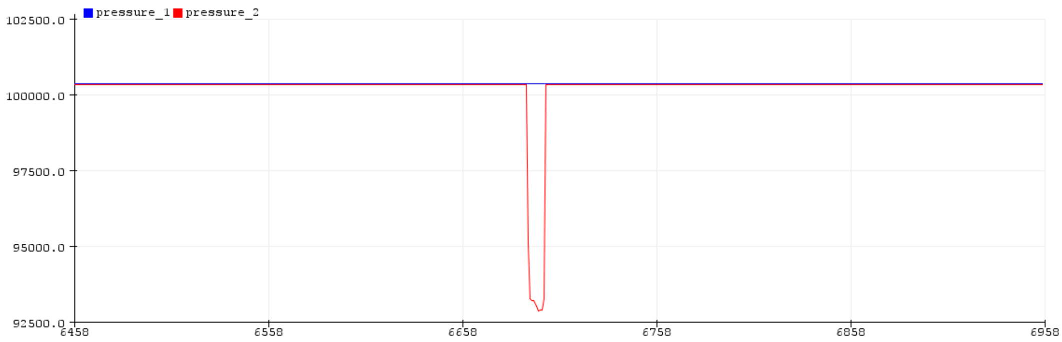

Figure 6: Response for sudden pressure change with filter disabled

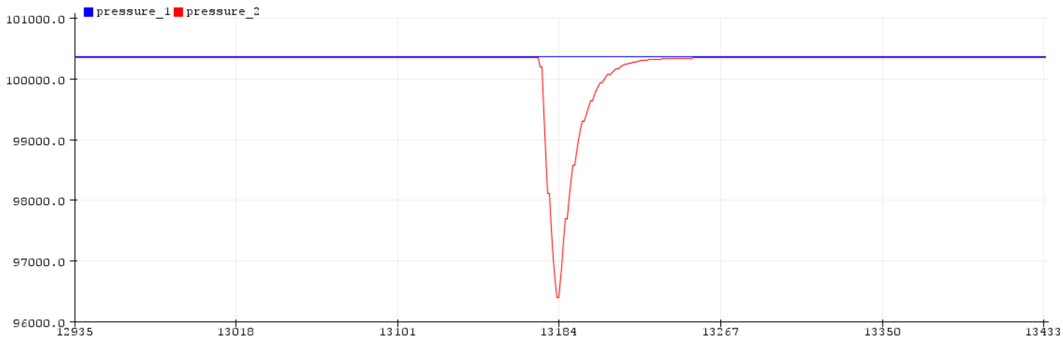

Figure 7: Response for sudden pressure change with filter storing 8 samples

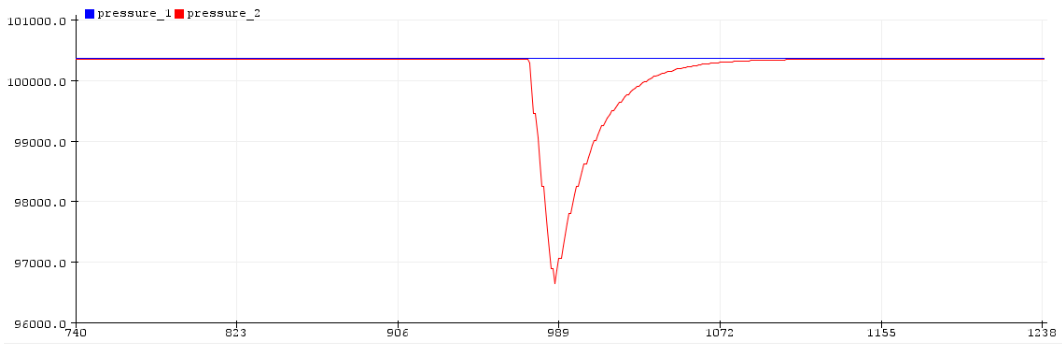

Figure 8: Response for sudden pressure change with filter storing 16 samples

Using filter slows down data significantly, but on the other hand measurement is much more stable for small differences in pressure. Finally a filter storing 8 samples was used as a compromise between quick response and stability.

8 Achieved results

8.1 Tests in the real-life environment

Tube was mounted on a side of a car. When car was moving, pressure in tube was generated. Ground speed was measured with GPS on a smartphone. Results are presented in charts on figures 9, 10 and 12.

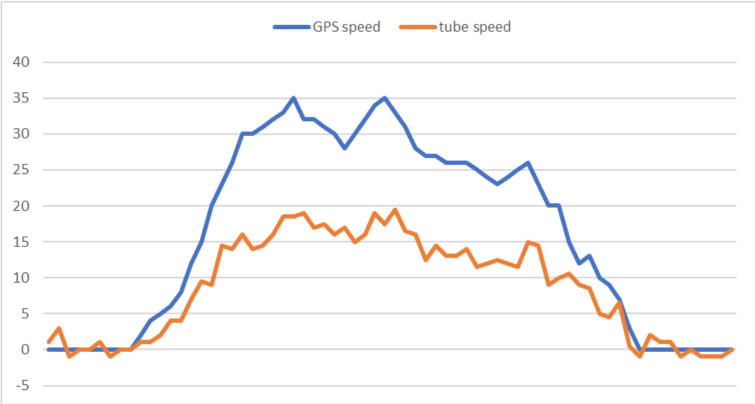

Figure 9: Speed from GPS and tube - 1st test

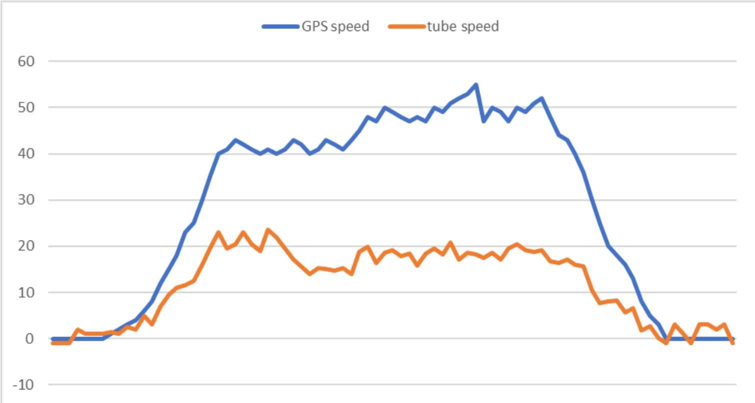

Figure 10: Speed from GPS and tube - 2nd test

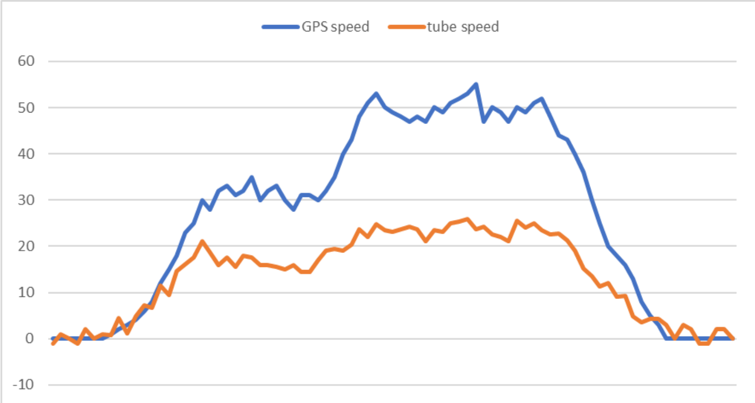

Figure 11: Speed from GPS and tube - 3rd test

It can be seen that speed measured by Pitot tube is always lower than reference speed measured by GPS. Speed ratio is not constant and thus it cannot be fixed by simply multiplying by a constant coefficient. Differences are probably caused by angle of tube in reference to air movement direction. Wind had a significant influence on a measurement results too and probably it is responsible for non-linear ratio of measured velocities. Though day was relatively windless, even small blows caused strong drops and increasements of measured vehicle speed.

8.2 Robustness for side wind

In this way a robustness of Pitot tube against angle of incoming air was tested. Test was performed in a room conditions (no external wind). As a source of constant air movement a hair dryer blowing cold air was used. Air was blown into a tube at different angles. Results are presented in table **??** and on a chart **??**

Angle [deg]	speed [km/h]
-90	-0.4
-60	4.2
-30	11.2
0	15.8
30	12.3
60	3.9
90	-0.6

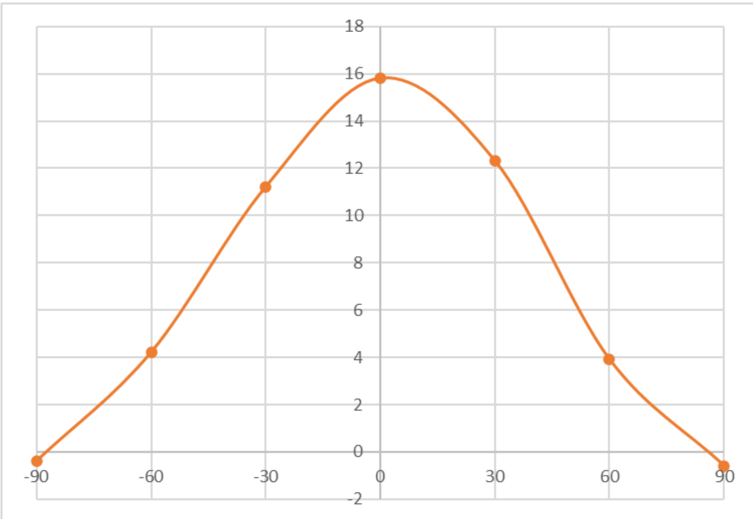

Figure 12: Speed in respect to angle of incoming air

Pitot tube returns different results for different angles of air movement. Interpolated plot of measured speed in respect to angle of air movement is similar to cosine. It can be assumed that Pitot tube captures correctly speed of air moving in parallel to the tube. If actual flow of air is not parallel to the tube, tube measures only $V_x = cos(\alpha) * V$ - component of velocity that is parallel.

9 Summary

Sensor interfacing with I^2C bus allows for simple and robust measurements. Assigning different I^2C bus to each sensor improves robustness and allows parallel communication. Filters embedded into sensors greatly improve stability, but slow down response for quick pressure changes. Using them increases stability.

Pitot tube measures only speed of air that is parallel to the tube. If actual flow of air is not parallel, it measures velocity component that is parallel to tube axis.

Tests in real-life scenario showed that speed of a vehicle measured by Pitot tube and GPS differ drastically. It can be caused by many factors, for example:

- tube axis not aligned with vehicle movement direction,
- air disturbances caused by vehicle's body,
- unpredictable wind speed and direction.

References

[1] Bosch Inc. *BMP280 Digital Pressure Sensor*. 2018.